ABSTRACT

We report a novel method for bubble or droplet displacement, capture and switching within a bifurcation channel for applications in digital microfluidics based on Marangoni effect, i.e. the appearance of thermocapillary tangential interface stresses stemming from local surface tension variations. High temperature gradients with a linear temperature profile is provided in situ thanks to shape optimization of the heating resistors. The experimental validation of the linear-like temperature profile within the cavity is carried out using a thermally sensitive fluorophore, Rhodamine B.

KEYWORDS: Thermocapillary actuation, shape optimization

INTRODUCTION

Digital microfluidics require element displacement by simple means featuring high integration rates. Within this context, the transport and handling of elements constitutes a problem [1]. To cite a few, available actuators are of electroosmotic [2], and dielectrophoretic [3,4] types. Mechanical actuation solutions exist as well [5], and these necessitate implementing a double-layer technology. The application of an external pressure source is also required.

This context has rekindled interest in the Marangoni surface effect, with the objective of developing actuation systems for moving bubbles or droplets. Most of reported papers deal with droplets in the presence of a triple line (droplet wets at least one wall). Models for the thermocapillary migration in the case of triple line has been proposed and confronted to experiments in a capillary [6,7] and over a substrate [8,9,10] (free surface plus triple line at the wall).

It is necessary to distinguish the cases involving a triple line from the ones involving a free surface. Actually, in the review of Squires and Quake [11] they clearly distinguish actuation along a triple line than an actuation along a free surface. They propose to denote the actuation along a triple line by thermowetting while thermocapillarity stands for actuation along a free surface. Our work concerns bubbles or droplet between two plates separated by a gap of the order of 20 microns, smaller than the element diameter. The continuous phase surrounding the element wets the substrate and the element is thus separated from the substrate by a thin liquid film. In that case, the physical mechanism involved in the element migration in a temperature gradient strongly differs from the case where the element is in direct contact with the substrate (no wetting film and a triple line) [11,12,13].

EXPERIMENTAL

The specificity of the reported actuation is that heating is provided by optimized resistor pattern [14] leading to a constant temperature gradient along a microfluidic cavity (figures 1 and 2). Briefly, in a first step the experimental set-up characteristics are described in order to set the physical parameters used for the optimization (dimensions of the different layers of the system, heat conductance of materials, heat flux at interfaces...). Indeed, the optimization aims to determine the geometry of the resistors while all other parameters are fixed. The resistor is composed of parallel wires connected in series. The width of the wires imposes the thermal losses and therefore the local heat density flux. The parameters to optimize are: the widths of the wires and the widths of the slits situated between them (these parameters allocate the number of wires placed at the bottom of the cavity). The optimization of the resistor pattern is achieved by coupling two numerical tools: a genetic algorithm, NSGAII, proposes a geometrical configuration of the resistors while the software COMSOL 3.4 evaluates the corresponding thermal response of the system including the physical parameters that were previously set. Once a geometry is set by the optimization (grey strips on figure 1) the thermal response has been measured using a thermally sensitive fluorophore, Rhodamine B, commonly used to measure temperature inside a microfluidic system [15,16]. After calibration, and using image processing it is possible to extract the temperature profile along the cavity which is found to be linear (figure 2).

Figure 1: Sketch of the cavity. Grey lines are the optimized resistor wires placed below the cavity.
Figure 2. Experimental evolution of temperature vs. position inside the cavity for different heating powers. L is the cavity size in the x direction.

Figure 3. Bubble velocity, for a solution of glycerol (5.8% w/w) and SDS surfactants (1.2 cmc i.e. 0.27 % w/w) and deionised water, rescaled by $f_u^* = (\partial \gamma / \partial x) / \mu u$ for a cavity thickness of 22 \( \mu \text{m} \) and (\( \bigodot \)) $\partial \gamma / \partial x = 0.26 \text{ Pa}$ (\( \bigtriangledown \)) $\partial \gamma / \partial x = 0.4 \text{ Pa}$ (\( \bigstar \)) $\partial \gamma / \partial x = 0.79 \text{ Pa}$ (\( \bigtriangleup \)) $\partial \gamma / \partial x = 1.54 \text{ Pa}$ for a cavity thickness of 37 \( \mu \text{m} \) and $\partial \gamma / \partial x = 1.54 \text{ Pa}$.

In this context, bubbles or droplets to be actuated entail a surface force originating from thermal Marangoni effect. It was found that the bubble/droplet (called further element) are driven toward high surface tension region, i.e. toward cold region, and the element velocity increases with both bubble radius $a$ and tangential stress $\partial \gamma / \partial x$ and decreases while increasing the cavity thickness $e$ (figure 3).

APPLICATIONS

Figure 4. Images of 300 \( \mu \text{m} \) diameter bubbles inside the switching device: left) without actuation, and right) with a 4 K/mm temperature gradient.

Taking advantage of these properties three applications are presented:
1) element displacement which velocity is characterized as sketched on figure 3
2) element switching: on figure 4, it is shown that bubbles naturally flow toward the left outlet channel (lower hydrodynamic resistance) when the power supply is OFF; while bubbles flow towards the right outlet channel as actuation is ON. The transient stage OFF/ON and ON/OFF lasts about 250 ms.
3) a system able to trap, and consequently stop on demand, the elements on an alveolus structure while the continuous phase is still flowing (figure 5).
The strength of this method lies in its simplicity: single layer system, in situ heating leading to a high level of integration, low power consumption (P<0.4 W), low applied voltage (about 10 V), and finally this system is able to manipulate elements within a flow velocity up to 1 cm.s⁻¹.

CONCLUSION

We have demonstrated the possibility to integrate in situ heating resistors able to generate a linear temperature profile within a microfluidic cavity. A bubble placed in such cavity undergoes Marangoni stress and is displaced towards cooler regions with a velocity proportional to both bubble radius and tangential stress, and inversely proportional to the cavity thickness. This actuation allows to manipulate bubbles in a microfluidic system: displacement, switching and trapping.

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REFERENCES


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